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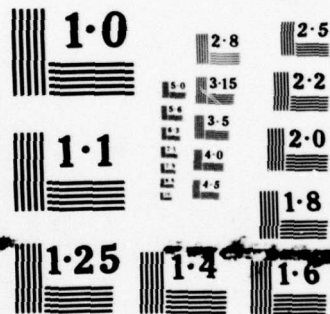
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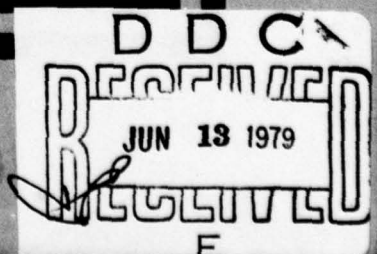
AGARD ADVISORY REPORT No. 137

**Technical Evaluation Report
on the
Fluid Dynamics Panel Symposium
on
Dynamic Stability Parameters**

NORTH ATLANTIC TREATY ORGANIZATION



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 ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT
 (ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Advisory Report No.137

TECHNICAL EVALUATION REPORT
 on the
 FLUID DYNAMICS PANEL SYMPOSIUM
 on
 DYNAMIC STABILITY PARAMETERS.

by

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Lockheed Missiles and Space Company, Inc.
 Sunnyvale, California, USA

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- Improving the co-operation among member nations in aerospace research and development;
- Providing scientific and technical advice and assistance to the North Atlantic Military Committee in the field of aerospace research and development;
- Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field;
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1. INTRODUCTION

The AGARD Fluid Dynamics Panel held a 3-day symposium on Dynamic Stability Parameters at the Greek War Museum, Athens, Greece, 22-24 May, 1978. Thirty-six papers were presented, compiled in AGARD Conference Proceedings No. 235 "Dynamic Stability Parameters." The meeting chairman was Dr. K. J. Orlik-Rückemann of National Aeronautical Establishment, Ottawa, Canada.

The program consisted of six sessions, Wind Tunnel Techniques I and II, Flight Testing Techniques Analytical Techniques, Motion Analysis and Nonlinear Formulations, and Sensitivity and Simulator Studies. Each of the five topics was introduced by a review by one or more invited speakers. A Workshop Session, a novel feature for an AGARD meeting, preceded the customary Round Table Discussion, which concluded the meeting.

2. PURPOSE OF THE MEETING

The aim of the symposium was to determine the needs for dynamic stability information, the form in which it should be presented, and the best means for obtaining such information. The space shuttle and high performance military aircraft are examples of modern aircraft that often fly at high angles of attack and are exposed to unsteady flow fields which may have significant effects on their motion characteristics. The unsteady flow fields involved usually result in highly nonlinear aerodynamic characteristics which may exhibit strong coupling effects between longitudinal and lateral degrees of freedom. A good knowledge of stability characteristics at high angles of attack is essential for a better understanding of the entire complex of stall/spin problems and could lead to a new formulation of the equations of motion.

3. DISCUSSION

Through a liberal use of invited papers the Program Committee, consisting of Mr. P. P. Antonatos (USA), M. L'Ing, de L'Armement A. Coursimault (France), Mr. J. L. Jones (USA), Dr. Ing B. Laschka (W. Germany), Professor E. Mattioli (Italy), Dr. G. G. Pope (UK), Dr. B. M. Spee (Netherlands), Dr. I. C. Statler (USA), and its chairman, Dr. K. J. Orlik-Rückemann (Canada), had made sure that the viewpoints would be heard not only from fluid dynamics analysts and wind tunnel test people but also from flight mechanics analysts and flight test people. This called for a rather broad program covering widely different topics. For that reason the individual sessions are reviewed as entities before a final evaluation is made of the meeting as a whole.

3.1.1 Wind Tunnel Techniques I

- (1) The first session on Wind Tunnel Techniques, chaired by J. L. Van Ingen (Netherlands) started appropriately enough with a review by the meeting chairman Orlik-Rückemann of the "Techniques for Dynamic Stability Testing in Wind Tunnels" which are used within NATO. The paper represented an extension of the thorough review of the North American dynamic facilities that the author had made earlier under contract to NASA (CR 114,583, 1973) to lay the foundation for a sound decision in regard to what dynamic testing capabilities would be needed for the space shuttle and future advanced aircraft. Special emphasis had been placed on the capability to determine the unsteady aerodynamics at high angle of attack, including cross-coupling between lateral and longitudinal degrees of freedom. The diversity of the techniques used was impressive. However, it was apparent that many problems associated with dynamic testing at high angles of attack, such as Reynolds number scaling, model support effects, and wind tunnel wall interference, still remained to be (re)solved.

- (2) Following this general overview were 12 papers (in the two combined sessions) in which the various NATO testing facilities were described in more detail. In "Nouvelle Technique d'Essais sur Maquettes Libres en Laboratoire pour la Détermination de Caractéristiques Aérodynamiques Instationnaires" by W. Charon and R. Verbrugge, the free flight test technique used at Institut de Mécaniques des Fluides, Lille, France, was described, in particular the motion analysis to extract the unsteady aerodynamic characteristics of the free flight model. The free flight test technique complements captive model testing. It eliminates (in most cases) the difficult problem of support interference and facilitates the simulation of gusts but introduces instead the difficult problem of analyzing six degrees of freedom vehicle motions.

- (3) In the next paper G. N. Malcolm and S. S. Davies discussed "New NASA-Ames Wind Tunnel Techniques for Studying Airplane Spin and Two-Dimensional Unsteady Aerodynamics." In order to study the aerodynamic behavior of airplane configurations at high angles of attack an advanced rotary-balance apparatus had been designed, which permitted measurements of the lateral-longitudinal cross-coupling for such coning motions as airplane spin. Early test results for a finned missile with a square cross-section body had shown significant effects of Reynolds number and the existence of discontinuous aerodynamic characteristics with spin-rate-sensitive hysteresis effects. These results amply demonstrated the need for the increased Reynolds number capability that the NASA Ames 12-foot pressure tunnel will provide with this new rotary rig, capable of simulating the spin rate parameters of most full scale spins. Still remaining to be determined is the support interference caused by vortices and wakes from the model interacting with the robust sting-strut support structure needed. The new dynamic rig for two-dimensional fluctuating pressure measurements could through a system of push-pull rods force an airfoil to describe oscillations in pitch around an arbitrary oscillation center, from $-\infty$ to $+\infty$, i.e., including pure plunging oscillations. Using the rig in the Ames 11 x 11 foot transonic wind tunnel will make it possible to duplicate the NLR tests (NLR TR 77090U, 1977) and extend them to higher Reynolds numbers. Also for this rig one will have to determine the support interference, in this case caused by the interaction between the airfoil and the side-plate boundary layer, which can be substantial because of the presence of flow separation.

- (4) Examples of the dynamic testing techniques used in UK were given by A. W. Matthews, who described the "Experimental Determination of Dynamic Derivatives due to Roll at B.A.C. Warton." Preliminary experimental side moment results obtained with this rotary derivative rig for a current combat aircraft showed large differences from flight test data already at low angles of attack. "These discrepancies have not been successfully explained at the time of writing..." according to the author. Provided that there was not a large mismatch in Reynolds number, one feels inclined to suspect that support interference caused the discrepancies.

- After this UK report it was time for the paper by X. Hafer on the "Wind Tunnel Testing of Dynamic Derivatives in W. Germany." Design details were given of the new oscillatory balances that had been developed since 1972 in a cooperative effort between research institutes and industry. Preliminary experimental side moment results deviated significantly from flight test results, possibly indicating the same type of support interference problem as in the previous paper. An evaluation had been made of the effect of damping and cross derivatives on the aircraft motion. It was found that longitudinal and lateral force derivatives ($C_{L\dot{\alpha}}$ and $C_{Y\dot{\alpha}}$, respectively) had a negligible influence.
- (6) In the following paper, "On the Test Procedures of the Derivatives Balances Used in W. Germany," by J. von der Decken, E. Schmidt, and B. Schulze, the data acquisition and reduction procedures used in these new facilities were described. The procedures selected were the result of joint efforts by ten (10) scientists from the aircraft firms Dornier, MBB and VFW-Fokker, the national research organization DFVLR, and the Technical Universities in Darmstadt and Bochum.

3.1.2 Wind Tunnel Techniques II

- The second session on wind tunnel techniques, chaired by B. Laschka (W. Germany) started with a description by Orlik-Rückemann of the "Experiments on Cross-Coupling and Translational Acceleration Derivatives" that had been performed at NAE, Ottawa, Canada, on a general aircraft-like configuration: a 7° ogive-cone with 45° truncated delta wing and fin. The aerodynamic derivatives obtained at $M = 0.7$ on a sting-mount model exhibited very strong nonlinearities at high angles of attack. In this α -range, $\alpha > 14^\circ$, the cross-coupling derivatives, which had been negligible at lower angles of attack, reached appreciable magnitudes, comparable to those of the regular direct derivatives. According to flow visualization results (not shown because of space limitation), these high- α characteristics are caused by separated flow and associated vortex shedding. The same basic geometry had also been used in a half-model plunging test to obtain the vertical acceleration derivative $C_{m\ddot{\alpha}}$. Here one has to consider side plate interference effects, especially at high α with the associated flow separation, as was also pointed out by the author.
- (9) Next E. S. Hanff, NAE, Canada revealed how he and Orlik-Rückemann had developed "A Generalized Technique for Measuring Cross-Coupling Derivatives in Wind Tunnels." In addition to the dynamic balances with which various cross-coupling derivatives could be measured, a separate multi-degree-of-freedom dynamic calibrator was developed to independently verify the validity of the experimental procedures used. In the calibrator the oscillatory aerodynamic loads acting on a model in a wind tunnel were simulated by electromagnetically induced loads acting on a calibrator frame, that was mounted on the dynamic balance in place of the model.
- (10) In "Détermination de Non-Linéarités de Stabilité Dynamique" Mr. X. Vaucheret, ONERA, France, showed how to treat mathematically various type of nonlinear characteristics. Of particular interest was the description of the frequency and amplitude behavior generated by a discontinuous restoring moment with associated aerodynamic hysteresis. This is a typical nonlinear characteristic generated by separated flow which often leads to limit cycle oscillations. Test results were shown for an ogive-cylinder-flare body at $M = 4.5$ demonstrating how the experimentally observed limit cycle behavior could be predicted. When roughness was applied in the nose region attached flow was established and the free oscillation damped to zero amplitude. - These results are typical for flared body testing from high subsonic to hypersonic Mach numbers and illustrate the problem of scaling dynamic wind tunnel data. Without roughness, flow separation may occur only in the wind tunnel test and not in full scale. On the other hand applying boundary layer tripping devices either completely eliminates the coupling existing in full scale flight between transition and vehicle motion (in the case of trip wires) or drastically changes it (in the case of distributed roughness which becomes more effective on the windward side with increasing α , whereas the natural crossflow effects promote transition on the leeward side).

- After this series of papers discussing national efforts, it was time to learn what P. Poisson-Quinton and M. Canu from ONERA, France, together with B. Laschka, B. Schulze, and W. Standacher from MBB, W. Germany, had found to be "Some Factors Affecting the Dynamic Stability Derivatives of a Fighter-Type Model." Schulze demonstrated in a series of slides how the addition of a strake (a highly swept inner delta wing) to the moderately swept wing of a fighter aircraft model dramatically improved the dynamic characteristics at high α . Poisson-Quinton then showed one of H. Werlé's excellent flow visualization movies which demonstrated and further illuminated some of the points made in Schulze's slide show.
- (12) In the following paper, "An Experimental Study of the Hypersonic Dynamic Stability of Pitching Blunt Conical and Hyperballistic Shapes in a Short Running Time Facility," by R. A. East, A. Qasrawi, and M. Khalid, University of Southampton, UK, it was demonstrated how valid dynamic test results could be obtained in an intermittent hypersonic tunnel that uses a light piston compression mode of operation. The results obtained for blunted cones agreed well with other available experimental data.
- (13) The last paper in this session "Unsteady Aerodynamics of Oscillating Containers and Application to the Problem of Dynamic Stability of Helicopter Underslung Loads," by A. Simpson and J. W. Flower, University of Bristol, U.K., presented results from a thorough investigation of a difficult problem. Because of their non-aerodynamic shape the containers experienced separated flow even at very low speeds. Consequently, the aerodynamic characteristics were very nonlinear and associated with aerodynamic hysteresis. As a result one degree of freedom limit cycle oscillations, of stall flutter type, were observed. Quasi-steady methods could not be used in the analysis because of the high reduced frequency associated with the low forward speed. (This is also the case when analyzing dynamic stall and associated stall-flutter of the helicopter blades.) The paper also showed an example of strong support interference. It occurred when the clumsy strut structure, supporting the sting, was too close to the model.

3.2 Flight Testing Techniques

- The first of two invited speakers in this session, which was chaired by P. Poisson-Quinton, ONERA, France, was P. M. Jeglum, Edwards AFB, USA, who with slides of past and present military aircraft provided a suitable background for his accounting of the "Air Force Flight Test Center Experience in the Identification of Stability and Control Parameters from Dynamic Flight Test Maneuvers." His conclusions were that increased aerodynamic sophistication will be needed in the design of future military aircraft.
- (14)

As had been promised by his forerunner, Kenneth W. Iliff, NASA Dryden Flight Research Center, USA, (15) did reveal much of the intricacies involved in the "Estimation of Aerodynamic Characteristics from Dynamic Flight Test Data." His very thorough review showed that so far almost all the work at the center had been confined to analysis of linear mathematical models. For cases where this model is correct they had had some success in determining cross-coupling effects, both aerodynamic and kinetic. When the nonlinear mathematical model was known, the analysis had given good estimates, but when it was not, as in the stall/spin case, useful results had not been obtained. Without a good physical insight into the flow phenomena involved, e.g., the various types of separated flow existing at high angles of attack, no meaningful estimates could be obtained from the analysis of flight test data. Thus, the flight data analyst needs to work closely together with theoreticians and wind tunnel test people. The general conclusion was that presently the existing problems are in the mathematical modelling, not in the parameter extraction technique.

(16) Next R. A. Whitmoyer, AFFDL, Wright Patterson AFB, USA, reported on the "Aerodynamic Interactions on the Fighter CCV Test Aircraft" YF-16 that had been observed in a 125-hour flight test program. The main problem had been encountered when using Direct Lift Control (DLC) in the pitch pointing mode at high angles of attack. The required trailing-edge up flap deflections had caused a severe loss in tail power, and resulted in limiting DLC application to below $\alpha = 18^\circ$. Direct Side Force Control (DSFC) was accomplished by means of coordinated deflections of ventral, vertical canards and the rudder. The addition of the canards reduced the static directional stability by 50% but did not significantly degrade the dynamic directional stability; it actually increased $C_{y\dot{\alpha}}$ for high angles of attack, probably because of favorable interference effects from the canard surfaces on the downstream main wing. The Relaxed Static Stability (RSS) limits for safe operation had also been investigated revealing the difficulties existing in realizing the maximum benefits for a practical fighter aircraft. The conclusion was that the CCV-concept rather than reducing had increased the demands on accurate definition of aerodynamic characteristics.

(17) After all this discussion of rigid aircraft aerodynamics, it was time for E. G. Rynaski to describe how he and his colleagues D. Andrisoni II and N. C. Weingarten at Calspan, USA, had accomplished the "Identification of the Stability Parameters of an Elastic Aircraft." Their approach had been to use FLEXSTAB computer program to obtain an initial definition of the equations of motions, including elastic degrees of freedom. By using phase variable transformations the mathematical model could be reformulated in a form that allowed piecemeal acceptance of parameters estimated from flight data. The ingenuity needed in this gradual updating of the initial mathematical description of the elastic airplane was described. The method permitted stability and control derivatives, as well as parameters describing flying qualities, to be expressed in a form that could be understood by both aerodynamicists and flight controls people. The results shown were for elastic responses to the rigid aircraft motion. - One would also be interested in knowing what effect ignoring elasticity has on the identification of rigid aircraft stability and control parameters from flight test data, a point raised later by P. P. Antonatos (USA) in regard to all "rigid body" test data.

(18) In the final paper in this session, "Nonlinear Parameter Identification and its Application to Transport Aircraft," by T. J. Galbraith and T. J. Petersen, Boeing, USA, it was shown how the difficulties encountered in identifying the nonlinear aerodynamic and kinetic cross-coupling experienced by the YC 14 aircraft in stalled flight had been overcome. Only by close cooperation between aerodynamicists and simulation people had it been possible to obtain credible parameter identification results.

3.3 Analytical Techniques

This session, chaired by G. G. Pope, RAE, Hants, UK, started with two invited papers which beautifully complemented each other, the first describing high- α phenomena that so far had defied a purely theoretical treatment, the second taking an inventory of the present status of unsteady aerodynamic theory. The first (19) paper, "A Survey of Analytical and Experimental Techniques to Predict Aircraft Dynamic Characteristics at High Angles of Attack," by A. M. Skow and A. Titiriga, Jr., Northrup, USA, dealt with such high- α flow phenomena as vortex burst, asymmetric body vortices, and wing stall, describing how they could cause various vehicle dynamics problems such as spin entry, wing rock and buffet, roll reversal and departure, yaw and pitch departures, as well as strong yaw-pitch cross-coupling. The problem viewed from the point of the vehicle designer was to first determine full scale behavior, using empirical theory based upon correlations between wind tunnel and flight test results, and then design a fix if needed, as in the illustrated case of asymmetric forebody vortex shedding. The described Shark Nose fix, consisting of a flattening of the fuselage nose with associated apex rounding (giving it a shark nose shape), completely eliminated the asymmetric forebody vortex shedding. It was a beautiful example of what can be accomplished when the flow phenomenon causing the problem is well understood. The authors emphasized that vast amounts of tunnel and flight test data are available which have not been fully analyzed and correlated, not even for individual aircraft, much less across the board. Across-the-board correlation efforts are made very difficult by the extreme configuration sensitivity of these high- α flow phenomena. However, this also makes the achievable gains in future military aircraft designs that much greater.

(20) In the second paper, "Presentation of Stability Derivatives in Missile Aerodynamics and Theoretical Methods for their Prediction," C. P. Schneider, Messerschmitt-Bölkow-Blohm BmbH, W. Germany, reviewed the open literature to determine what theoretical methods exist that can predict the dynamic stability derivatives for geometries of interest to the missile designer. In the company report, Ref. 10, an equally thorough and equally valuable survey is made of existing experimental data. The results of the surveys are summarized and categorized in tabular form, where the availability of various derivatives is shown. It is also indicated what the relative importance of a certain derivative is to the missile design.

(21) Following these two broad overviews, R. Roos, NLR, Netherlands, reviewed "The Use of Panel Methods for Stability Derivatives," delineating the complications involved when using non-planar instead of planar panel methods, emphasizing that in many cases the cheaper planar methods will give satisfactory results. Use of panel methods for both elastic and rigid body dynamics will facilitate analysis of the complete aircraft (e.g., as in Paper 17).

(22) Next W. H. Hui, University of Waterloo, Canada, described "An Analytical Theory of Supersonic/Hypersonic Stability at High Angles of Attack," which could predict the negative pitch damping measured on a

wedge at $M = 1.75$. The inviscid theoretical results showed that the effect of Mach number on the high- α pitch damping of wedges, flat plates and delta wings becomes negligible for $M > 3$.

- (23) The following paper, "Identification of Unsteady Effects in Lift Build Up," by P. Mereau, R. Hirsch, G. Coulon, and A. Rault, ADERSA/GERBIOS, France, showed that the lift buildup measured on a subscale aircraft in general agreed well with theory. However, the measured step response of the wing lift to flap motion started out at twice the theoretical value.
- (24) In "Effect of Flow Separation Vortices on Aircraft Unsteady Aerodynamics" by L. E. Ericsson and J. P. Reding, LMSC, USA, it was shown how simple analytic means had been developed for prediction of the unsteady longitudinal aerodynamics of slender wings up to large angles of attack. Using static experimental data as an input also the nonlinear unsteady aerodynamics of the Space Shuttle Orbiter could be predicted, including the effects of flow separation and associated vortices. It was shown that because of convective time lag effects the separated flow affects static and dynamic stability in opposite ways, that is, the separated flow effects are statically stabilizing and dynamically destabilizing, or vice versa.
- (25) Concluding the session was a paper by R. Bernier, Galtit, USA, and G. V. Parkinson, University of British Columbia, Canada, showing how "Oscillatory Aerodynamics and Stability Derivatives for Airfoil Spoiler Motions" could be determined using linearized incompressible potential-flow theory.

3.4 Motion Analysis and Nonlinear Formulations

- This session, chaired by J. L. Jones, USA (Chairman, FDP), started also with two invited papers, the first presenting a general theoretical treatment, the second giving examples of the difficulties that may be encountered by the practicing motion analyst.
- (26) In "The Role of Time-History Effects in the Formulation of the Aerodynamics of Aircraft Dynamics" M. Tobak and L. B. Schiff, NASA-Ames RC, USA, added the final touch to their well-known previous work in this field by including time history effects to arrive at a formulation general enough to allow for the discontinuous aerodynamic characteristics usually experienced at high angles of attack because of flow separation.
- (27) In "Mathematical Models of an Aircraft for Extreme Flight Conditions (Theory and Experiment)" H.H.B.M. Thomas and G. Edwards, RAE, UK, first discussed possible simplifications of the Tobak-Schiff general formulation before selecting a completely different formulation which had been developed at B.A.C. (Warton), U.K. In it the perturbation analysis is made from a steady state condition which includes the effect of high roll rates represented by a term that depends only on angle of attack (in addition to roll rate) whereas also side slip is an important parameter in the steady-state coning motion used by Tobak and Schiff. Comparison with free-flight test data for a quarter scale aircraft model showed the UK-formulation to be inadequate. The authors hoped that a perturbation analysis from a steady state coning motion could be made in the near future. Such a formulation was presently not possible with the aerodynamic test data available in UK, but will be when data obtained with the new rotary rigs (described at this meeting) become available. The sensitivity study showed the motion to be insensitive not only to the side force derivatives C_{Yp} and C_{Yr} but also to the cross-coupling derivative C_{Yq} .* These theoretical results should be viewed with caution in view of the mismatch between predicted and experimentally observed motions, as was pointed out by the authors.
- (28) Next J. Roskam, University of Kansas, USA, showed how to answer the question, "Linear or Non-Linear Analysis Methods - When and How?", using two hypothetical airplanes for illustrative purposes, one (Airplane A) being a typical large, variable sweep supersonic transport configuration and the other (Airplane B) being a typical high performance, swept-wing fighter. Lyapunov stability theory was used to determine when linear and locally linearized methods could be used, and energy methods were used to solve the nonlinear equations of motion. As Tobak and others also have found, Roskam found the usefulness of linearized methods to be especially limited in the presence of cross-coupling between longitudinal and lateral degrees of freedom. Thus, as expected, linear methods worked for Airplane A but not for Airplane B in many of the examples chosen.
- (29) In his paper J. Kalviste, Northrop, USA, concentrated on the nonlinear analysis of "Aircraft Stability Characteristics at High Angles of Attack" showing how to define stability criteria for the fully coupled six-degrees-of-freedom case. The criteria had been validated by a complete six-degrees-of-freedom perturbation analysis and by flight test results. Even the nonlinear, non-zero lateral aerodynamic characteristics generated at zero sideslip, e.g., by asymmetric forebody vortices, could be accounted for. One flaw with the present formulation is that it does not account for dynamic cross-coupling effects. Hopefully, work in progress will eliminate this deficiency.
- (30) The next paper, "Expressions des Forces Aérodynamiques Non Linéaires en Vue des Etudes de Dynamique du Vol" by M. Scherer, ONERA, France, reviewed the nonlinear analysis methods that had been developed during recent years in order to handle the nonlinear aircraft dynamics experienced in high- α flight.
- (31) In his paper "Nonlinear Oscillations at High Incidence" G. D. Padfield, RAE, UK, assumed that the airplane was flying close to a stability boundary, determined by linear methods, and used Nayfeh's method of multiple scales to perform a nonlinear perturbation analysis that could describe the transient oscillatory growth to a limit cycle condition.
- (32) The last speaker in this session, P. C. Parks, Royal Military College of Science, UK, used a simplified ballistic analysis to describe "The Dynamic Stability in Flight of Spinning Blunt Body Projectiles." The projectile was can-shaped, a bluff cylinder, and had the same separated flow problem as the box-shaped container discussed by Simpson and Flower in Paper 13. Thus, the $C_m(\alpha)$ -curve was S-shaped, giving three equilibrium yaw angles for the spinning projectile. This resulted in some interesting vehicle motion possibilities.

*It should be noted, however, that the C_{Yq} value used was an order of magnitude smaller than the maximum measured in the tests reported in Paper 8.

3.5 Sensitivity and Simulator Studies

- The session was chaired by P. P. Antonatos, USA, a native of the host country. As in the earlier sessions, an overview was provided through an invited paper, in this case "Results of Piloted Simulator Studies of Fighter Aircraft at High Angles of Attack," by J. R. Chambers, W. P. Gilbert, and L. T. Nguyen, NASA-Langley, USA. Various examples were given showing how nonlinear aerodynamic characteristics could explain nose slice, wing rock, adverse yaw, and other problems encountered by an advanced fighter maneuvering at high angles of attack. In particular, the great importance that roll damping plays in the wing-rock phenomenon was emphasized. While airframe modifications and use of control interconnects sometimes had provided solutions, more often than not the only recourse had been maneuver limiting. It was pointed out how configuration dependent these high- α phenomena are. Consequently, the relative importance of static and dynamic stability parameters had varied considerably, the simulator studies showing the dynamic stability parameters to be of little importance for some configurations and very important for others. The extreme importance of identifying the true nature of the aerodynamic high- α characteristics was emphasized, especially in regard to existing discontinuities and aerodynamic hysteresis effects.
- (34) In the next paper, "Sensitivity of Aircraft Motion to Aerodynamic Cross-Coupling at High Angles of Attack," coauthored by W. H. Curry, Sandia, USA, and K. J. Orlik-Rückemann, NAE, Canada, linear and locally linearized representation of the aerodynamic characteristics were used to investigate the effect of aerodynamic cross-coupling on the motion of an aircraft at high angle of attack. A representative military aircraft had been chosen for the physical characteristics and the traditional aerodynamic derivatives were based on measurements for such an aircraft. However, because they were the only experimental results available, the cross-coupling derivatives used were those measured on a generalized aircraft-like configuration (presented in Paper 8 by the second author). When judging the results of the study, one has to keep this mismatch in mind. The study showed that the most important aerodynamic cross-coupling is the effect of pitch rate on lateral characteristics, whereas the effects of yaw and roll rates on longitudinal characteristics were insignificant. That is, the rolling and yawing moments due to pitch rate were larger than those due to roll and yaw rates, respectively. Using locally linearized derivative values greatly increased the effect of cross-coupling on the vehicle motion. The study showed the dynamic cross-coupling terms to have a larger effect on the vehicle motion than the static terms. Although the results may be distorted due to the lack of matched aerodynamic cross-coupling derivatives the authors felt that the results should be quite representative of a present-day fighter flying at high angles of attack.
- (35) The same mismatched cross-coupling derivatives had been used by R. W. Butler and T. F. Langham, ARO, USA, in their study of "Aircraft Motion Sensitivity to Variations in Dynamic Stability Parameters," and the results were, therefore, very similar in many respects. Their results showed that when the cross-coupling derivatives C_{lq} and C_{nq} were of a magnitude four (4) times as large as the lateral derivatives C_{lr} and C_{nr} they become of equal importance to the vehicle motion. Using hypothetical separate values for acceleration and rotation derivatives the authors had found that the acceleration derivatives $C_{\dot{\alpha}}$ and $C_{\dot{\beta}}$ have a strong effect by themselves on the aircraft lateral/directional motion characteristics. Consequently, they should be separated from their rate counterparts, C_{nr} and C_{lr} , in motion analyses. They had analyzed two different aircraft, a Fighter/Bomber and an Attack Type, and had found the general results of their sensitivity study to be independent of the aircraft considered. This particular finding is contrary to the findings of other investigators and is probably caused by the fact that the two aircraft studied were geometrically very similar and would, therefore, have similar aerodynamic characteristics.
- (36) In the last paper of the session D. E. Johnston, Systems Technology, USA, talked about the "Identification of Key Maneuver-Limiting Factors in High Angle of Attack Flight." One identified important factor was the cross-coupling effect of angle of attack on rolling moment, which caused a decrease of the roll damping for the F-4 aircraft and led to wing rock. The limit-cycle characteristic of the F-4 wing rock was determined by the cross-coupling effect of yaw on the pitching moment derivative C_{mp} , a cross-coupling effect found to be insignificant in the preceding two papers. An interesting feature of C_{mp} is that it is insensitive to the sign of β and therefore responds at twice the β -frequency. It was pointed out in the discussion that the inertia coupling also gives this double frequency response. However, according to the author the rates were so small that the kinematic cross-coupling was negligible, which is somewhat surprising and counter to the experience of others (see Paper 15).

3.6 Workshop Session

This was a new feature for an AGARD meeting, although it has been tried with good success at various AIAA Specialists meetings in USA. Probably because of the novelty for AGARD, there were only four contributors. First, L. E. Ericsson, LMSC, USA, showed that transonic sting interference may present problems even when testing a pointed, sharp cone at small angles of attack. The problem arises because the attainable high Reynolds number at transonic speeds in most wind tunnels is such that boundary layer transition will occur on the aft body. The transition location is then largely guided by the position of the plunging sting relative to the base shoulder, causing associated distortion of the aerodynamic characteristics. The static stability is decreased slightly while the dynamic stability may be increased as much as 100%.

Next B. Krag, DFVLR, Braunschweig, W. Germany, described how vehicle parameter identification in gusts was accomplished by dynamic simulation in a wind tunnel. A remotely controlled subscale model was suspended in a frame allowing vertical translation and rotation in pitch, yaw, and roll. A gust generator consisting of two movable flaps could produce various types of gust profiles at frequencies up to 15 Hz. For lower frequencies, $f \leq 6$ Hz, the distortion of the gust profile during the convection downstream to the model was of negligible magnitude.

Next S. M. Bogdonoff, Princeton University, USA, described the communication breakdown between fluid dynamicists and motion analysts that this meeting had revealed to him. As the aerodynamic nonlinearities experienced at high angles of attack are caused by flow separations they are very sensitive to Reynolds number, wind tunnel turbulence, and other ground testing characteristics.[#] The absence of any mentioning of this fact by the users of wind tunnel data in motion simulations had disturbed him greatly. In regard to

[#]Such as support interference

another problem not discussed in the meeting, that of thrust modelling, he was persuaded by comments from the audience that it was of less importance than he had anticipated.

Finally Mr. H.H.B.M. Thomas, RAE, UK, showed the film about preparation of subscale models for flight tests that he had not had time to show during his presentation of paper 27 earlier.

3.7 Round Table Discussion

The panel discussion was opened by the chairman, K. J. Orlik-Rückemann (Canada), who, after having laid down the ground rules for the discussion, gave us his thoughts about Wind Tunnel Techniques. He listed three criteria which a good wind tunnel test technique should meet. (1) The measurement of any particular parameter should be independent of the mathematical modelling, that is, there should be a direct relation between the stability parameter to be determined and the quantity being measured. In the indirect approach the value for the parameter will always be dependent upon the equations of motions used to arrive at it. Hence, it is dependent upon the mathematical modelling, and any later change in the equations of motion will invalidate the results. (2) The accuracy of the measurements should be acceptable, i.e., as high as is required for the particular simulation in mind, and not necessarily as high as possible. (3) The technique should be applicable to experiments at the higher Reynolds numbers that future facilities will provide with associated very high loads. In addition, he also expressed his concern in regard to static and dynamic support interference, wind tunnel flow unsteadiness and tunnel wall interference. Although the discussion that followed was rather lively, it essentially elaborated on the points made. Only in regard to putting a number on the accuracy required for dynamic stability derivatives were there distinct differences of opinion.

Next panel member to be heard from, K. W. Iliff, NASA-Dryden, USA, described how in Flight Testing Techniques the number of unknowns that the flight test program has to determine has grown with time because of the increasingly complex criteria that a modern high performance aircraft has to satisfy. He emphasized that the complete definition of the aircraft mathematical model through flight tests will always depend on analytic and wind tunnel test results. Thus better and more frequent communication between the experts supplying the mathematical models and the specialists conducting the aircraft flight test would be needed. Until these Utopian conditions materialize, flight data analysts would continue to use ad hoc techniques, such as data fit by means of power series expansion. Iliff had a list of six criteria that he wanted to apply to any modelling done without phenomenological basis. (1) Higher order error statistics must indicate that the estimates are valid. (2) The quality of the fit must be very good, and even small discrepancies must be explained. (3) The simplest mathematical model that fits the data must have been used. (4) A consistent trend must result for each estimated coefficient as each independent variable is changed. (5) A plausible physical explanation for each resulting model should be found. (6) The resulting mathematical model must be evaluated on a completely independent set of data. Finally, he raised the question if it might not be worthwhile to apply flight test data analysis techniques to dynamic wind tunnel tests. Had anyone made a tradeoff study between the one parameter wind tunnel test with its complicated test set-up and a multiple parameter test with a simpler test rig but requiring a more complex data reduction analysis? The general consensus of opinion was that one needed the one parameter test when one did not have a good understanding of the physical flow phenomena causing the nonlinearities, as is presently the case in regard to cross-coupling effects at high angles of attack. That is, one needs first to build up the individual building blocks before going into a more complex multi-parameter analysis. This would be particularly true for the low Reynolds number environment presently supplied by most wind tunnels, with extrapolation of results to full scale presenting a big problem.

The third panel member, A. Titiriga, Northrop, USA, in his discussion of Analytical Techniques zeroed in on the aircraft design problem. With configurations becoming more complex it will be more important than ever to provide the tools needed by the engineer to successfully design future highly maneuverable airplanes within given time and money constraints. The tools could be provided through correlation of analytical, wind tunnel and flight test data, not only aircraft by aircraft but also across the board. It would be especially valuable to establish how configuration sensitive are the various aerodynamic mechanisms and what is the minimum sophistication required to describe them adequately for design purposes. The following discussion was generally supportive and extended some of Titiriga's ideas.

H.H.B.M. Thomas, RAE, UK, the fourth panel member, who promised to be brief in his comments about Motion Analysis and Nonlinear Formulations, only commented that it may often be necessary to leave the general formulation by Tobak, et al., and develop special approximate models that could solve the practical problem at hand.

Finally, it was time for the last panel member, J. R. Chambers, to give his slide-illustrated comment on Sensitivity and Simulator Studies. He outlined future research requirements in regard to dynamic stability of aircraft at high angles of attack. The high- α aerodynamics are very configuration sensitive, down to small details on each airplane. Considering the rather drastic configuration changes that will take place in the future, today's solutions are unlikely to apply to tomorrow's airplanes. He argued that we know very little about the effect of non-zero side slip on important dynamic parameters, and pleaded that we strive to obtain as complete a set of aerodynamic data as we can with existing limited wind tunnel techniques. He was especially emphatic about the need to obtain aerodynamic data at the proper Reynolds number and Mach number, expressing his expectation for what cryogenic wind tunnels and magnetic suspension techniques would be able to offer in that regard. He finished with a personal wish that the complacency in regard to high- α aircraft aerodynamics and dynamic stability parameters that developed in USA after the Korean war would not be repeated again just because several current fighters through a combination of good applied research and ad hoc design have obtained outstanding high- α characteristics. He hoped that with the recognition of the unique new configurations that are coming forward it will become clear that we cannot afford a lessening of our efforts in dynamic stability research if we are ever to understand the high- α behavior of future military aircraft. Chambers had made his points very well and got no arguments from the audience, only a reminder that for commercial and carrier-based aircraft ground interference is an important part of the high- α problem.

Chairman Orlik-Rückemann, in declaring the panel discussion concluded, indicated that although there had been some mixed feelings in regard to the timeliness of a meeting like this when he had proposed it two years earlier, the very good response to the call for papers, the excellent attendance, and the lively discussions that had taken place all convinced him that the symposium had been a considerable success. In particular, it had demonstrated that there was a great need for wind tunnel, flight test, analytical and flight mechanics people to meet and exchange viewpoints thereby achieving a better understanding of the problems that are facing us all.

Finally, J. L. Jones, NASA Ames, USA, chairman of the AGARD Fluid Dynamics Panel, declared the meeting adjourned.

4. CONCLUSIONS

The biggest service this meeting on Dynamic Stability Parameters did to the AGARD technical community may well be that it revealed that large communication gaps still exist between the various groups responsible for the design of present and future advanced performance aircraft which must be able to carry on sustained operations at high angles of attack. Because of the magnitude and complexity of the tasks involved the various specialists tend to be absorbed by their own problems and have little time over for interdisciplinary dialogue. It was apparent that this meeting filled a void. As so often is the case, the very difficulties that make communication so hard also make it essential that communication does take place. What follows is a list of the problems I became aware of during the meeting - not only through the many excellent official presentations and discussions but also to a large extent through private conversations with many meeting participants.

- o Configuration Sensitivity. The new unusual aerodynamic characteristics encountered at high angles of attack are generated by various forms of flow separation. Consequently, the high- α aerodynamics are extremely configuration sensitive. Even a boundary layer trip can in many cases qualify as a geometric configuration change. Thus, apparently similar configurations can exhibit widely different high- α characteristics.

- o Reynolds Number Effects. As the high- α characteristics are dominated by separated flow effects, they become very dependent upon Reynolds number. This makes the use of subscale test data very difficult, especially in regard to dynamic characteristics. It is well documented that there is a strong coupling between the boundary layer transition process and the vehicle motion. This coupling affects the unsteady aerodynamics significantly even for attached flow and has a much stronger effect in the presence of separated flow. Thus, one cannot use boundary layer tripping devices if one wants to simulate full-scale unsteady aerodynamics in a subscale model test.

- o Dynamic Test Techniques

Because of the nonlinear character of the high- α characteristics, it is important to have a direct, single-parameter relationship between the quantity measured and the stability parameter to be determined. Even though the standard type derivative measure obtained in such a dynamic test may vary with both amplitude and frequency, thus strictly speaking invalidating the derivative concept, the measure obtained is descriptive and will together with appropriate static data make it possible to define uniquely the mathematical model that correctly describes the nonlinear high- α dynamic characteristics. Theoretical models established in this fashion may be applied as building blocks in the mathematical modelling of multi-degrees-of-freedom motion. The unknown character of the aerodynamic high- α characteristics including cross-coupling effects necessitates using a dynamic calibrator of some type, e.g., as is described in Paper 9.

- o Support Interference

In captive testing model support interference presents a problem even at low angles of attack. At high angles of attack with associated separated flow vortices and wakes, the downstream support system is an even larger source of interference. It has already been shown that a strut support provides a formidable static support interference at high angles of attack. The problem is compounded when one considers that based upon past experience the dynamic support interference can be large even when the static interference is negligible. All the high- α dynamic test rigs discussed at this meeting could cause significant support interference. Although the interference characteristics are different for sting, strut and side plate supports, they can all be significant.

- o Nonlinear Aerodynamics

The nonlinear characteristics at high angles of attack are generated by separated flow. When the dominating effect comes from leading or trailing-edge vortices, there is an α -range in which series expansion methods are valid, because the aerodynamics are continuous. However, when the vortices burst, or a sudden change of separated flow pattern or extent occurs, the aerodynamic characteristics become discontinuous, and are often associated with hysteresis effects, which all are characteristics that can not be modelled by the popular series expansion approach. Thus, it is essential that one understands the physical background for the nonlinear characteristics. For discontinuous aerodynamic characteristics the dynamic stability parameter (the damping derivative) measured in a wind tunnel test will have a major component that is inversely proportional to the oscillation amplitude. If static (rate-independent) hysteresis is present, that same component will also be inversely proportional to the reduced frequency. In this case standard type locally linearized methods will not suffice. The correct treatment is not mathematically difficult, but one must know when to apply it.

- o Cross-Coupling

There was convincing evidence presented in this meeting that when analyzing the aircraft characteristics at high angles of attack one can no longer decouple lateral and longitudinal degrees of freedom.

Although the results of the various linearized analyses have to be viewed with a certain degree of caution because of the highly nonlinear nature of the high- α characteristics, this does not change the fact that for the amplitudes and reduced frequencies for which the used aerodynamic parameters apply, the cross-coupling effects were found to be very significant. The largest effect was that of pitching on lateral characteristics, whereas in general the effect of yawing and rolling on longitudinal characteristics were found to be modest. It should be emphasized that this applies only to the particular types of configurations investigated. In view of the extreme configuration sensitivity no general statements can be made.

o Mathematical Modelling

There is no doubt that when one wants to model the high- α aerodynamics of an advanced aircraft one needs a formulation as general as that presented by Tobak and Schiff, which can handle discontinuities and hysteresis effects. However, the practical application of such a formulation hinges strongly on the availability of the mathematical building blocks discussed earlier. There probably are many cases of general interest for which alternate, simpler formulations will suffice. The problem presently is to obtain the aerodynamic parameters in the form needed to verify the mathematical modelling through comparison with multi-degrees-of-freedom test results. The mathematical modelling is the pacing factor in present simulation and flight data analysis for aircraft maneuvers at high angles of attack.

o Dynamic Stability Parameters

Throughout the meeting the question came up as to the relative importance of static and dynamic stability parameters, including cross-coupling terms. Invariably the answer seemed to be that this depended entirely upon the configuration, a seemingly unimportant change swinging the importance from dynamic to static and vice versa. This may be understood if one considers the fact that the high- α aerodynamics are dominated by separated flow effects. It is by now well established that for rigid body dynamics (and elastic vehicle dynamics of modest reduced frequency) the separation-induced aerodynamic forces affect static and dynamic stability in opposite ways, i.e., the effect can be statically stabilizing and dynamically destabilizing, or the other way around, as was demonstrated in Paper 24. Which it is depends on such configuration details as the location of separation source and responding aircraft surface in relation to the center of gravity. If one makes the rather safe assumption that it is the adverse effect that receives the main attention, one can see why it depends so much on configuration details whether dynamic or static stability parameters are important. However, because of the amplification through convective time lag effects the dynamic effects of separated flow are much greater than the static effects. Consequently, one should be most concerned about the dynamic stability parameters of an aircraft operating at high angles of attack. Hence, the topic of this meeting could not have been more appropriate.

o Credibility/Communication

Because of all the problems listed above it is quite possible, even likely, that flight test engineers and vehicle designers can have experimental results that prove to them that wind tunnel test engineers and analysts, publishing results showing large cross-coupling effects, adverse vehicle dynamics, etc., do not know what they are talking about. Thus, it is vitally important that communication channels are kept open and that every effort is made to improve the interdisciplinary dialogue, as was emphasized by Iliff throughout the meeting.

5. RECOMMENDATIONS

The present meeting took the first step towards establishing a mechanism through which the various groups involved in the aerodynamic design of aircraft and missiles can exchange information that will lead to a more efficient use of available resources. This should only be the beginning, the first meeting in a regular series. The many problem areas uncovered in this meeting should be investigated and reported on next time. The following recommendations are made:

- a) Initiate a cooperative research program to investigate the difficult problem of support interference. Because of the complete dependence of motion simulations, flight test data reduction and sensitivity studies on wind tunnel test data, this problem of support interference must be solved before meaningful progress can be made.
- b) Stress the importance of obtaining the following complementary data in all high- α testing.
 1. Flow visualization data
 2. Static data for increasing and decreasing parameter values (α , β , η , etc.) in order to define aerodynamic hysteresis.
 3. Static and dynamic stability data for the same test conditions in the same wind tunnel with the same support geometry.
 4. Test data for the widest possible Reynolds number range including effects of boundary layer tripping devices.
- c) Investigate the scaling problem for high- α dynamic (and static) data.
- d) Promote more extensive analysis of available high- α experimental data.
- e) Continue work on formulation and verification of mathematic modelling of high- α unsteady aerodynamics including the effects of cross-coupling and the effect of discontinuous and hysteretic static aerodynamic characteristics.

- f) Establish a complete set of aerodynamic data to determine the importance of cross-coupling for a few basic configurations.
- g) Measure the effects of small geometric perturbations from these basic configurations to establish in a systematic manner the configuration sensitivity of high- α aerodynamics including cross-coupling effects.
- h) Attempt to generate design guidelines for aircraft operating at high angles of attack.

The ultimate goal is, of course, to obtain the detailed understanding of steady and unsteady high- α aerodynamics needed for successful design of future advanced aircraft and aerospace vehicles.

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